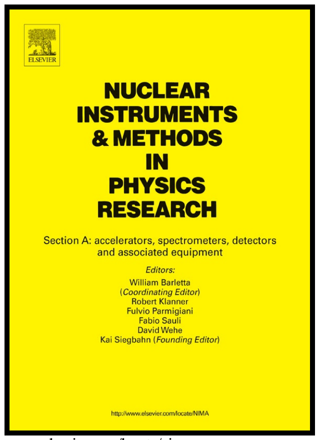
The kaon identification system in the NA62 experiment at the CERN SPS

NA62 Collaboration

DOI:
10.1016/j.nima.2016.05.128

The kaon identification system in the NA62 experiment at the CERN SPS

Nicolas Lurkin



www.elsevier.com/locate/nima

PII: S0168-9002(16)30530-7
DOI: http://dx.doi.org/10.1016/j.nima.2016.05.128
Reference: NIMA59031

To appear in: *Nuclear Inst. and Methods in Physics Research, A*

Received date: 23 March 2016
Revised date: 30 May 2016
Accepted date: 30 May 2016

Cite this article as: Nicolas Lurkin, The kaon identification system in the NA6: experiment at the CERN SPS, *Nuclear Inst. and Methods in Physics Research A,* http://dx.doi.org/10.1016/j.nima.2016.05.128

The kaon identification system in the NA62 experiment at the CERN SPS

Nicolas Lurkin[a,*], On behalf of the NA62 Collaboration[1]

[a]*School of Physics and Astronomy, University of Birmingham, B15 2TT, United Kingdom*

Abstract

The fixed target experiment NA62 at CERN aims at measuring the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$, whose branching ratio is of the order of 10^{-11}. The main challenges faced by the experiment to achieve a 10% precision measurement are the required beam intensity and background rejection factor. The differential Cherenkov detector KTAG must be able to tag charged kaons in an unseparated hadron beam with an average particle rate of 750 MHz, of which 45 MHz are kaons, with a time precision of at least 100 ps and an efficiency higher than 95%. The additional pion contamination must be kept lower than 10^{-4}.

The RICH has been designed to separate charged pions from muons in the momentum range $15 < p < 35$ GeV/c, contributing to a further muon rejection factor of 100. In order to match the upstream and downstream activity, a time resolution similar to the one of KTAG must be achieved. The RICH is also used as a primitive trigger generator for the level-0 trigger system.

The construction and commissioning of both detectors was completed and their performances were studied during the 2014–2015 runs.

Keywords: Cherenkov detectors, Fast timing, Photomultiplier, NA62, KTAG, RICH

*Corresponding author

Email address: `nicolas.lurkin@cern.ch` (Nicolas Lurkin)

[1]Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome LS, Rome TV, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver

1. The NA62 Experiment at the CERN SPS

NA62 is a fixed target Kaon decay experiment located at the CERN SPS. The main goal is to measure the branching fraction of the ultra-rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ with a precision of $\sim$10% and a ratio signal/background > 10. This process plays a key role in the search for new physics. With a dominant contribution coming from the short-distance t quark, and small c quark and long-distance corrections, this decay is theoretically very clean. The standard model prediction is computed to an exceptionally high degree of precision [1]:

$$Br(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (9.11 \pm 0.72) \times 10^{-11}$$

The main uncertainty arises from the CKM matrix elements, and the pure theoretical uncertainty is at the 1% level. An experimental measurement of the branching ratio at a similar level of precision can constrain new physics scenarios because many of them predict effects on this branching ratio.
On the experimental side, the best available measurement [2]:

$$Br(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = 1.73^{+1.15}_{-1.05} \times 10^{-10}$$

is extracted from the 7 $K^+ \to \pi^+ \nu\bar{\nu}$ candidate events observed by the E797 and E949 experiments at the Brookhaven National Laboratory. The achieved precision is not sufficient, however, to be a significant test of new physics.
The aim of NA62 is to collect around 50 $K^+ \to \pi^+ \nu\bar{\nu}$ events per year of data taking with $\sim$10% accuracy and less than 10% background. To achieve this ambitious goal, two challenges must be faced: a large sample of kaon decays must be considered and a sufficient fraction of the background must be rejected. The former is fulfilled by a high intensity beam providing 4.5×10^{12} K^+ decays/year within the 10% detector acceptance. The beam is extracted from the primary 400 GeV/c SPS beam line impacting on a Beryllium target. The secondary beam reaching the experiment is an unseparated hadron beam at 75 GeV/c with a momentum bite of 1%. The composition of the beam is roughly $K^+ \sim$ 6%, $\pi^+ \sim 72\%$, $p \sim 22\%$. The second requirement is to achieve a rejection

factor greater than 10^{12} on other kaon decays acting as background to the measurement. This is accomplished by a combination of kinematic rejection, efficient particle identification and veto systems and a good time resolution to match upstream and downstream activity. The kinematic rejection is mainly driven by the performances of the GigaTracker spectrometer for beam particles and the Straw spectrometer for the charged decay products.

2. The Kaon Identification System

As the beam entering the experiment has a total particle rate of 750 MHz and contains only $\sim 6\%$ K^+ it is important to tag them to reduce the event rate. The Kaon identification system is the first detector, located at the beginning of the experiment and is expected to sustain a flux of 45 MHz of kaons while providing a positive identification efficiency greater than 95% and less than 0.1% mis-tagging probability. It should also provide a time resolution better than 100 ps for the downstream event matching.

The CEDAR/KTAG system is an upgrade of the Cherenkov Differential counter with Achromatic Ring focus West (CEDAR West) build in the 1970s for the SPS beam lines [3]. The vessel is filled with nitrogen as radiator gas. The Cherenkov light is transported outside the gas volume by the internal optics through a diaphragm and 8 quartz windows. The optics comprise a spherical Mangin mirror and elements for focusing and correcting chromatic errors. The optical axis must be precisely aligned with the beam axis. This also requires the beam divergence to be small: of the order of 100 µrad. The design of the detector only allows to select a fixed Cherenkov angle and the aperture of the diaphragm permits to tune the tolerance around that angle. As the beam is monochromatic, it is sufficient to adjust the gas pressure to select the particle mass to which the CEDAR is sensitive. The CEDAR is enclosed in a cooled, thermally insulated volume and the environmental conditions are constantly monitored.

2.1. The KTAG upgrade

The original version of the CEDAR is neither able to withstand the rate requirements nor to yield the desired time resolution. The KTAG upgrade designed to improve the performance is twofold: an upgrade of the light collection and detection and the replacement of the entire readout.

The original photomultipliers placed after the exit windows were replaced by focusing lenses and convex spherical mirrors reflecting the light radially. Thanks to this change the detection planes were moved farther from the axis, leaving more space and allowing to spread the light on wider areas. The photon rate per unit area is lower, reducing the strain on the readout. The detection planes are instrumented with 8 insulated and cooled light boxes. The entrance of the box is formed by a matrix of closely spaced light collection cones covered with aluminized Mylar, machined in spherical convex aluminium plates. An array of 48 small, fast Hamamatsu photomultipliers (32 of type R9880 in the centre and 16 of type R7400 on the edges) is placed at the exit of the cones. The box also contains the high voltage distribution board and the front-end electronics.

A custom printed circuit board extracts a differential signal from the anode and the last cathode of the photomultiplier. Each light box houses a mother board with 8 NINO ASIC chip [4] mezzanines. They perform a fast Time-over-Threshold on the 64 input channels and output a Low Voltage Differential Signal (LVDS). A splitter board collects the signals from all sectors and redistributes them on the readout based on the common acquisition system of the experiment. The TEL62 mother board [5] is used as integrated trigger and data acquisition and hosts 4 daughter boards (TDCB). Each of these TDCB is equipped with 4 high-performance analogue time to digital conversion (HPTDC) chips with 32 channels each [6]. The times of both the leading and trailing edges are recorded, providing the width of the signal time for slewing corrections in the analysis. KTAG uses 6 similarly equipped TEL62 boards where the channels are distributed in such a way that the data rate is equalized amongst them. The maximum sustainable rate is ~ 5 MHz per PMT.

The detector was tested on a beam line at CERN in 2011. The CEDAR was equipped with both its old readout, and prototypes of the new photomultipliers and front-end electronics. The results of this test were used as input to carry out detailed simulations of the transport of Cherenkov photons inside the CEDAR, using all the available information concerning the optical components. As seen in Figure 1, the separation in angular distribution of the Cherenkov photons on the diaphragm is sufficient to isolate the kaons and pions. A diaphragm aperture of 1.5 mm provides the required kaon efficiency and pion rejection. More details can be found in [7].

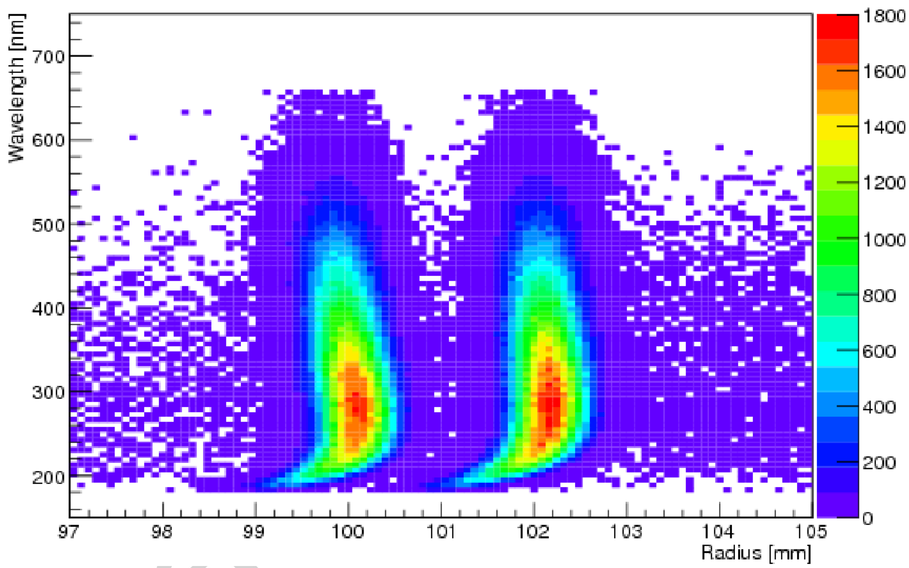


Figure 1: Distribution of Cherenkov photons on the diaphragm plane in N_2. The accumulation around 100 mm is due to kaons while the one around 102 mm is due to pions.

2.2. Performance

The KTAG performance was studied on multiple occasions. A first test of a partially equipped KTAG was performed during a technical run with beam at 1% intensity in 2012. Only 4 sectors were instrumented with 32 PMTs of type R7400 each. A pressure scan was performed. The extrapolation of the pion contamination under the kaon peak is done by looking at the tails of the pion peak. It permits to estimate the pion mis-identification probability, and is found to be $\sim 10^{-4}$. The single photon time resolution after corrections is measured to be $\sigma_t(\gamma) = 280$ ps.

The commissioning was completed during the 2014/2015 physics run. The KTAG was fully instrumented and the expected performance has been confirmed. An average of $N_\gamma = 20$ photons per kaon are detected. The time resolution for kaons is $\sigma_t(K) = \sigma_t(\gamma)/\sqrt{N_\gamma} = 70$ ps. The efficiency is studied by reconstructing a sample of $K^+ \to \pi^+\pi^0$ using only information from the Liquid Krypton calorimeter (LKr). These events are compared with the fraction of events for which the CEDAR does not have a matching candidate as a function of the number of fired sectors. The efficiency is better than 95% for 5 or more sectors fired. Finally a pressure scan was performed at the beginning of 2015 for different diaphragm apertures. The result is presented in Figure 2. A diaphragm aperture of 1.5 mm and a pressure of 1.745 bar have been chosen in order to maximise the kaon identification efficiency.

3. The RICH detector

Many background events contain muons and the experiment needs a reliable way of identifying them. This is the purpose of the RICH detector. It needs to provide a muon suppression factor of better than 100 for charged tracks in the range $15 < p < 35$ GeV/c. As for the CEDAR the time resolution on the pion crossing time must be of the order of 100 ps. It must also provide a level-0 trigger for charged tracks.

The detector is a Ring Imaging Cherenkov detector placed at the exit of the vacuum volume. The vessel is 17.5 m long and the diameter varies from 4.2 m at the entrance to 3.2 m at the exit. It is closed at each end by thin (2–4 mm) aluminium windows. A beam pipe starts at the entrance window and exits at the downstream side through an O-ring allowing longitudinal movement.

In order to be fully efficient at 15 GeV/c the Cherenkov threshold should be at 12.5 GeV/c, which corresponds to a refractive index of $(n - 1) = 62 \times 10^{-6}$.

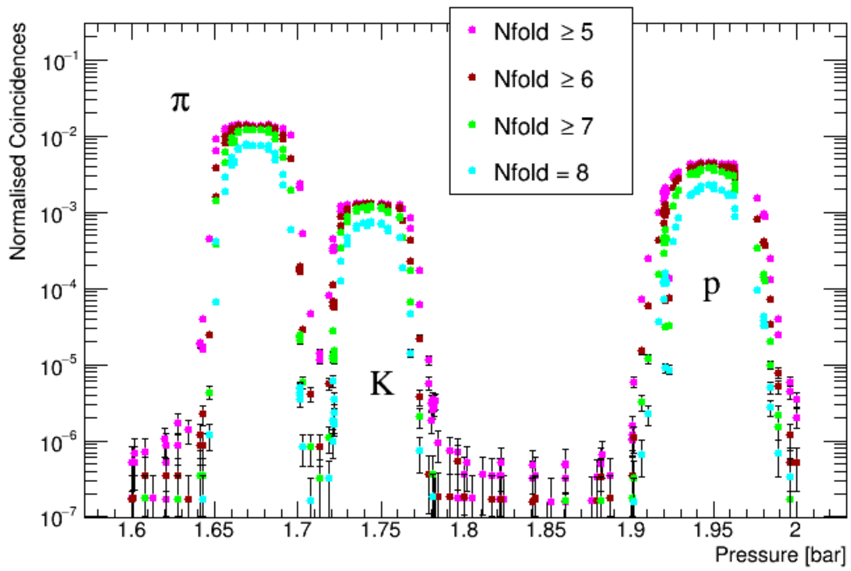


Figure 2: Pressure scan at 1.5 mm diaphragm aperture in log scale. The 1st peak corresponds to the pion peak, the 2nd to the kaon peak, and the 3rd one to the proton peak.

Neon has been chosen as radiator gas and has two advantages. Its refractive index at atmospheric pressure matches almost exactly the requirements and it is sensitive to wavelengths above 190 nm, rendering the detector insensitive to the main impurities (H_2O and oxygen). All other impurities, like CO_2, are naturally not present and can be kept low. The gas is kept at 990 mbar in the sealed volume without continuous renewal. Small losses due to leaks are compensated by occasionally topping up.

An array of hexagonal mirrors of 35 cm side length (18 full hexagons and 2 semi-hexagonal ones with a circular opening around the beam pipe) are placed on the downstream endcap to reflect the light on the photo-detectors. They are spherical with a radius of curvature of (34 ± 0.2) m and a focal length of 17 m. They are made of 2.5 cm thick glass with an aluminium coating and a thin dielectric film for protection and to increase the reflectivity. Their average reflectivity is better than 90%. To reduce the material budget, a 5 cm thick aluminium honeycomb structure is supporting them. They are connected to the support by a dowel with a spherical head inserted in a hole drilled on the non-reflecting surface at the back of the mirrors. Two thin aluminium ribbons keep them in position and are connected to piezo-electric actuators allowing remote control for fine alignment. To avoid light reflection on the beam pipe, the left and right subset of mirrors are oriented towards the detection spots on their respective sides.

Thanks to the larger radius at the entrance window, the photon detection system is located outside of the acceptance and concentrated on two aluminium disks on the left and on the right of the beam pipe. The detection planes support a total of 1952 Hamamatsu R7400U-03 photomultiplier tubes placed behind a light collection system made of Winston cones covered with aluminized Mylar foils. They are separated from the neon by 1 mm quartz windows.

Similarly to the KTAG, the custom made amplifiers provide differential output signals, which are fed to 64 front-end boards. Each of these accommodates 32 channels and uses 4 NINO ASIC chips in time-over-threshold mode. The LVDS output signal is sent to TEL62 boards as already described in 2.1. The readout is performed by four TEL62 and a fifth one is used to generate level-0 primitives using the digital OR of 8 channels provided by the NINO chip.

3.1. Performance

The RICH was fully commissioned during the 2014–2015 run. A sample of positive pions from $K^+ \to \pi^+\pi^0$ is selected. A π^0 is reconstructed using the information from the LKr and the missing mass of the charged track must correspond to the π^+ mass. Detected photons belonging to the same Cherenkov ring are divided into two groups and the time difference of the average between the two groups is plotted. The ring time resolution is ~ 70 ps, half the sigma of that curve. The average number of detected photons varies between 8 and 16 as a function of the track momentum.

A preliminary mirror alignment was performed with a laser after their installation. However, a fine alignment should be performed using data. The Straw spectrometer was not fully operational in 2014 and could not provide tracking, delaying the mirror fine-tuning to the 2015 run. The track properties are measured in the Straw detector and the expected ring centre (p_{track}) in the RICH is predicted by extrapolating the track position on the mirror plane. The position of the centre of the ring (p_{fit}) is fitted from the RICH hits. The track and ring are matched by requiring the distance between these two positions to be smaller than 20 mm

$$d_{\text{fit}-\text{track}} = |p_{\text{fit}} - p_{\text{track}}| < 20 \text{ mm}$$

The mirror fine alignment is performed by minimising $d_{\text{fit}-\text{track}}$ for the rings that are fully contained in a single mirror.

During the 2015 run, the RICH showed a good separation between pions, muons and electrons in the range of interest ($15 < p < 35$ GeV/c) as seen in Figure 3. It has been assessed that the RICH reached a muon rejection factor of 50 and a pion detection efficiency of 83%. The ring radius resolution is dominated by the mirror alignment and a final alignment campaign foreseen in 2016 will push the RICH to its design efficiency.

4. Conclusion

The NA62 experiment uses two Cherenkov detectors for particle tagging and identification. The KTAG detector is an upgrade of a differential Cherenkov detector (CEDAR West) whose purpose is to tag 45 MHz of charged kaons in a beam of 750 MHz of particles with 100 ps time resolution. The RICH provides separation between pions and muons in the momentum range between 15 and 35 GeV/c with a similar time resolution.

The installation of both detectors has been completed. A first data taking campaign was performed in 2014–2015 during which these detectors were commissioned. The displayed performance in terms of time resolution, identification efficiency or contamination either reached the design values or was close to the expectations but some improvements are still possible during the upcoming runs.

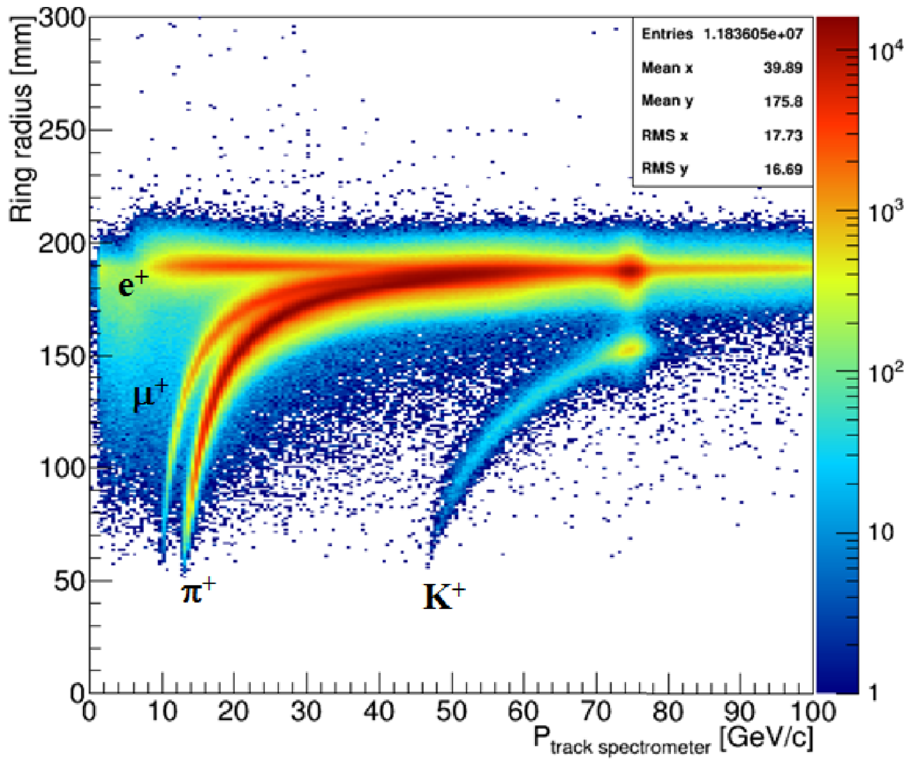


Figure 3: Track distribution as a function of reconstructed momentum and fitted ring radius. The RICH shows good separation between particles in the range $15 < p < 35$ GeV/c. A small beam component can also be observed at 75 GeV/c

References

[1] A. J. Buras, D. Buttazzo, J. Girrbach-Noe, R. Knegjens, $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L \to \pi^0\nu\overline{\nu}$ in the Standard Model: status and perspectives, JHEP 11 (2015) 033.

[2] A. V. Artamonov, et al. (E949 Collaboration), New measurement of the $K^+ \to \pi^+\nu\overline{\nu}$ branching ratio, Phys. Rev. Lett. 101 (2008) 191802.

[3] C. Bovet, R. Maleyran, L. Piemontese, A. Placci, M. Placidi, The Cedar Counters for Particle Identification in the SPS Secondary Beams: A Description and an Operation Manual, CERN 82-13 (1982).

[4] F. Anghinolfi, et al., Nino: an ultra-fast and low-power front-end amplifier/discriminator ASIC designed for the multigap resistive plate chamber, Nucl. Instrum. Meth. Phys. Res. A 533 (2004) 183 – 187.

[5] B. Angelucci, E. Pedreschi, M. Sozzi, F. Spinella, Tel62: an integrated trigger and data acquisition board, in: Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2011 IEEE, 2011, pp. 823–826. doi:10.1109/NSSMIC.2011.6154547.

[6] J. Christiansen, HPTDC High Performance Time to Digital Converter, Technical Report, CERN, Geneva, 2004. URL: http://cds.cern.ch/record/1067476, version 2.2 for HPTDC version 1.3.

[7] E. Goudzovski, et al., Development of the kaon tagging system for the na62 experiment at cern, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 801 (2015) 86 – 94.